SUPER-ABSORBENT POLYMER BASED FIRE RETARDANT

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Abstract

In this project, we develop a SAP based wildfire home protection strategy. The strategy is design to increase the odd for house to survive in a wildfire and is made up of two parts: the preparation of SAP suspension and the design of a sprinkling system. We will also introduce the channels for a normal houseowners to purchase all the supply and the way to assemble and use the whole system. A cost accounting is also included in this project to help the houseowners to manage their budgets.

Primary Reader and Advisor: Marc Donohue

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Content

List of Tables

List of Figures

1 Introduction

In recent years, wildfire has aroused great concern in the world. Regions like the U.S.A, South America, Australia, Europe, etc which have a large landscape of forests have been prone to catastrophic wildfires and experienced severe loss of lives and economy. For example, California surfed the largest wildfire season recorded in California's modern history in 2020. Five of the top 20 largest California wildfires fires occurred, with a total of 4.2 million acres burned, more than 10 thousand structures destroyed and 31 people dead [Cal Fire, 2020]. Furthermore, the Australia’s 2019-2020 bushfires, which is also declared as the ‘worst wildlife disasters in modern history’, scorched more than 46 million acres of land, took the lives of 33 people, and destroyed more than 3,000 homes [van Eeden et al., 2020]. Thus, forest wildfire has became a great threat to local economies and personal safety.

Figure 1.1 2020 wildfire in Australia(left) and California(right) [Abbot, 2020 Mulkern,2020]

1.1 Wildfire and Human Activities

The frequency and severity of wildfire have been deeply influenced by human activities, directly or indirectly. Anthropogenic climate change leads to an increase in temperature, an insufficient rainfall, and the aridity of vegetation, which are favorable conditions to wildfire. The fire season now starts earlier and last longer than before, and the fire is also bigger. A report indicated that the average area affected by wildfire in western united states each year has extended almost 50 times larger from 1972 to 2012, and the fire season also grew nearly 4 times longer over the same period [Westerling, 2016]. Another report founded that nearly 55% of this increase in fire area can be attributed anthropogenic climate change [Abatzoglou, 2016]. With the continued warming of the whole planet, it is obviously to foresee a more and more severe wildfire threat in the future.

Another factor results in the growing loss caused by wildfire is the expansion of wildland-urban interface. Wildland-urban interface (WUI), where human developments are tied with and benefited from the undeveloped wildland, has become one of the most favorable types of residence zone in the united states. A 2018 report shows that WUI areas have grown from 581,000 to 770,000 km^2 in 1990 to 2010 and more than 30% of American family choose to settle in WUI [Radeloff et al., 2018]. Although the natural's gift of WUI provided a mentally and physically comfortable environment for the residents, the wildfire risk in WUI can not be ignored. The intermixing or contact of natural environment and houses or other developments creates a desirable environment for wildfire to grow and thus leads to a high wildfire risk. Also, the frequently human activities in WUI areas also increase the number of man-made wildfires, which is the major type of wildfire that threaten homes in the united states [Mietkiewicz et al., 2020]. As the result, wildfire management and mitigation has become a great trial not only to the government and houseowners in WUI, but also to the whole united states.

1.2 Wildfire Home protection strategies

An important part of wildfire management currently using in the united states is mandatory public evacuation. This approach is commonly used because of its benefit to minimize the casualties in wildfire. However, building loses, to some extent, are enlarged when using this approach [Stephens et al., 2009]. As no more than 10% of houseowners in high wildfire risk areas purchase the wildfire insurance [Gan et al., 2014], the building loses will usually cause deeply financial and psychological damage to these houseowners. In this way, many researchers have been working on the wildfire home protection plans and introduced several practical systems [McFarlane, 2011 Ager,2015]. Several states such as California and Colorado even state several laws to ask the new-building house to build with fire-resistant materials.

Figure 1.2 Ember storm in wildfire [Photo Source: Josh Edelson/Getty Images]

Three major causes of home ignition in wildfire are radiant heat, direct flame contact, and embers. While radiant heat and direct flame can cause only an ignition when the fire is close enough to a combustible material or the radiant heat is high enough, embers are light enough to be transported by wind and can ignite the houses far from the main body of the wildfire. As the result, Embers cause the majority of wildfire home ignition and more than 50% of home loss in wildfire can be blamed to embers [Apostol, 2018]. The current wildfire home protection strategies are also designed to protect property from embers.

There are two kind of wildfire home protection strategies: home hardening and fire-retardant based defense systems. Home hardening means to increase the resistance of house itself to the wildfire and try to minimize the chance of ignition. The commonly used home hardening techniques are replacing exterior surface of house with fireproof materials, replacing or installing exterior vents, and creating defensible space. The hardened home have been proofed to have a higher chance of survival in the wildfire [Quarles, 2010].

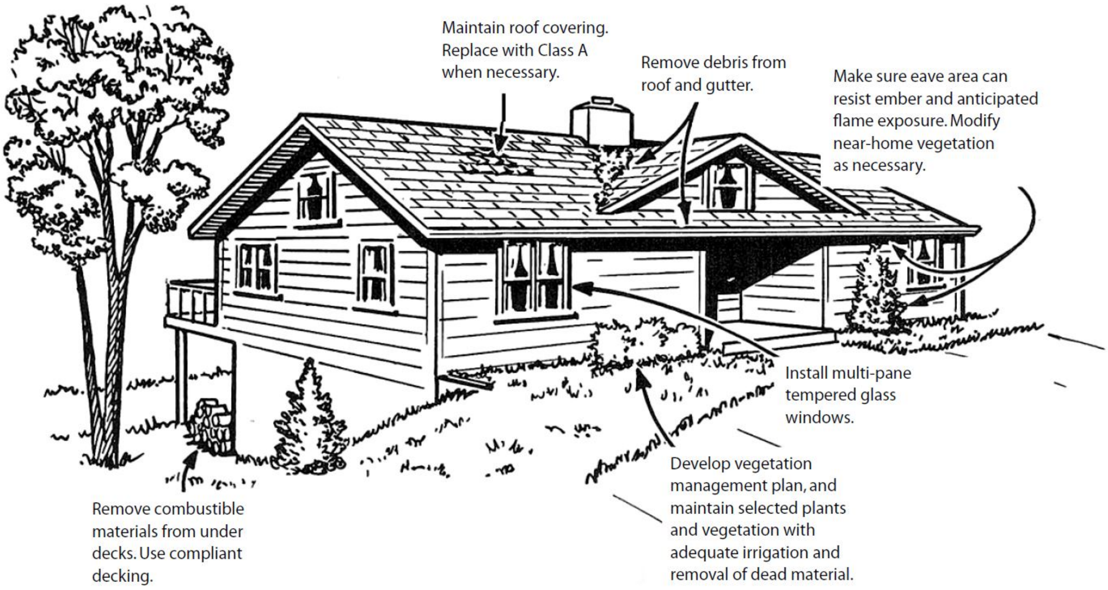


Figure 1.3 Guidelines for home hardening [Quarles, 2010]

Another possible method for wildfire home protection is fire-retardant based defense systems. These systems are self-contained system with isolate water source and backup power installing at the exterior of the house. When the wildfire comes, the system can be trigged manually or automatically and will spray water and fire retardant product mixture to cover and hydrate the house and surrounding areas, providing an additional protection to the coming wildfire. Several companies such as Colorado FireBreak and Frontline are providing the installation of this kind of system.

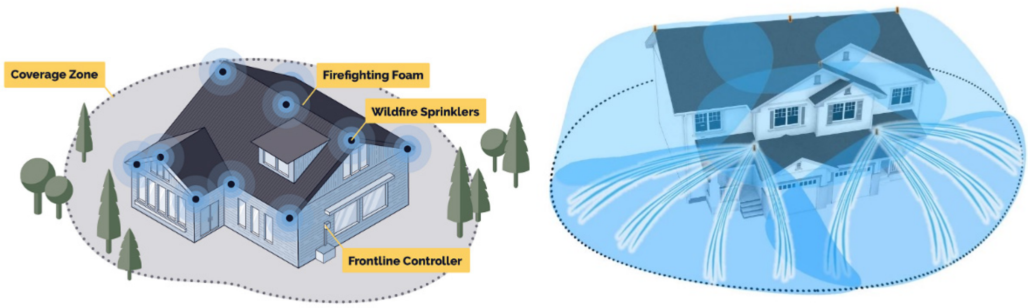


Figure 1.4 Example of fire-retardant based defense systems

Both strategies can be used to prepare home for wildfire. However, the weakness of them are the relatively high cost and long working hours to implant the strategies. For an average 2,200 square foot house, the average cost for home hardening is about 24 thousand dollar and several weeks are needed to do with the whole project [Penman, 2017]. The fee to install the basic fire-retardant based defense systems starts at $14,000 and more complex and powerful systems could be more than $100,000 [Chiment, 2020]. The high cost and questioning on the effectiveness of the system lead to a relatively low implantation rate of the wildfire risk-mitigation and nearly 85% of houseowners in high wildfire risk area do not take enough wildfire risk-mitigation actions [Brenkert-Smith et al., 2012]. As more than 40 million families are still under the threat of the wildfire, to find a cost-effective, easy-to-implement wildfire home protection strategy seems to be necessary and an urgent need.

1.3 Super Absorbent Polymer

Super absorbent polymer (SAP) is a kind of polymers with high water absorption and swelling capacity. Sodium polyacrylate is an example of SAP. It is crosslinked networks of flexible polymer chains. The polymer chains are shrunk before absorbing water. When water comes into contact with polymer chains, these chains are expanded, and water is trapped tightly within networks forming a hydrogel. A Sodium polyacrylate can absorb 800 times water to its weight in deionized and distilled water and 300 times in tap water [Migon et al., 2017].

Figure 1.5 SAP (left) and hydrogel formed by SAP (right) [Photo source: Ritchey/Wikipedia]

Water has been used for extinguishing fire and preventing the spread of the fire for centuries because of its high specific heat and large latent heat of vaporization. However, since water is a liquid and it does not have a large viscosity, water itself is hard to stay on the vertical surface such as walls and tends to run off to the ground. This somehow limits the application of water and causes significant waste of water source and manpower in firefighting.

To address the flaw of water in firefighting, water additives such as surfactant, blowing agent, and SAP are added to the water to endow the mixture suitable properties for firefighting. SAP relying on its low price, nontoxicity, biodegradability, and high water absorption capacity becomes one of the most popular firefighting water additives. However, the dry, solid, granular nature of SAP limits its application on standard firefighting equipment and specially-made pumps and nozzles are needed to directly use the dry polymer in firefighting applications. A potential way to address this problem is to disperse the SAP into a liquid phase and made it into a dispersion similar to paint [Edwin, 2003]. The liquid form dispersion can provide flowability and dispersibility which are desirable for firefighting applications.

1.4 Problem Statement

As mentioned in the previous section, wildfire management and mitigation has become a global trial. To develop a cost-effective, easy-to-implement wildfire home protection strategy seems to be necessary and an urgent need. SAP becomes the first candidate of the fundamental of the new strategy because of its low price, nontoxicity, biodegradability, and high water absorption capacity.

In this project, we develop a SAP based wildfire home protection strategy. The strategy is design to increase the odd for house to survive in a wildfire and is made up of two parts: the preparation of SAP suspension and the design of a sprinkling system. We will also introduce the channels for a normal houseowners to purchase all the supply and the way to assemble and use the whole system. A cost accounting is also included in this project to help the houseowners to manage their budgets.

2 Solution

The whole strategy is consisted of a SAP suspension and a sprinkling system. The suspension function as the carrier of the active ingredient, SAP, and will mix with the water under the control of the sprinkling system. The forming hydrogel will then be sprayed on the surface and surrounding of the target structure, providing a temporary enhancement to the wildfire resistance of the house. The total fee to implant the whole strategy is around $3,000, and the time needed, including the time for the preparation of SAP suspension and spraying, is about 1 day.

2.1 Preparation of SAP Suspension

The formulation of the SAP suspension refers to the content disclosed in the U.S. Patent No. 7189337B2 [Edwin, 2003]. The formulation of the SAP suspension is 38.0 wt. % ground sodium polyacrylate (average particle size lower than 100 microns), 2.3 wt. % sorbitan monooleate (span 80), 0.6 wt. % triton X-100, 1.7 wt. % fumed silica, 57.4 wt. % canola oil. Take the preparation of 500g suspension as an example:

In a large beaker, stir in 11.5g span 80 and 3.0g triton X-100 into 287.0g canola oil. Then progressively add 190g ground sodium polyacrylate powder into the oil mixture, keep stirring until get a homogeneous suspension. Finally, slowly stir in 8.5g fumed silica, keep stirring until all the fumed silica is dispersed in the suspension and there is no white lumps remaining. The finished SAP suspension should be a homogeneous glue like whitish yellow liquid.

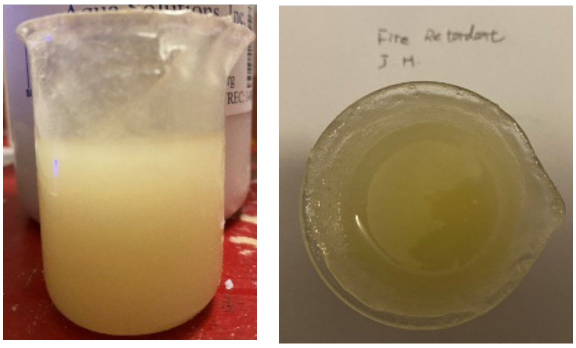


Figure 2.1 SAP Suspension

In the SAP suspension, canola oil is the carrier of the SAP, it can be replaced by mineral oil or other vegetable oil with the same volume without influence the effectiveness of the suspension. Span 80 is the dispersant agent, it can help the SAP particles disperse in the liquid phase, other low HLB surfactant can be the potential substitution of span 80, but further research is needed to confirm the influence. Triton X-100 presents as the wetting agent, it can help the mixing of water and suspension. Finally, fumed silica is the suspending agent, it increases the stability of the suspension.

2.2 Sprinkling system

The structure chart of the sprinkling system is shown in the figure 2.2.

The sprinkling system is built up with three parts: water supply system, suspension supply system, and spray system. The water supply system includes a water source and a pump for the water. The water source can be municipal water supplies, natural source such as river and lake or the water stored in private location such as swimming pool and water tank. Never use a water with high electrolyte concentration such as sea water since the presence of the electrolyte will weaken the water absorption capacity of SAP and finally reduced the effectiveness of the fire-retardant gel layer. The choice of the water pump will be discussed later.

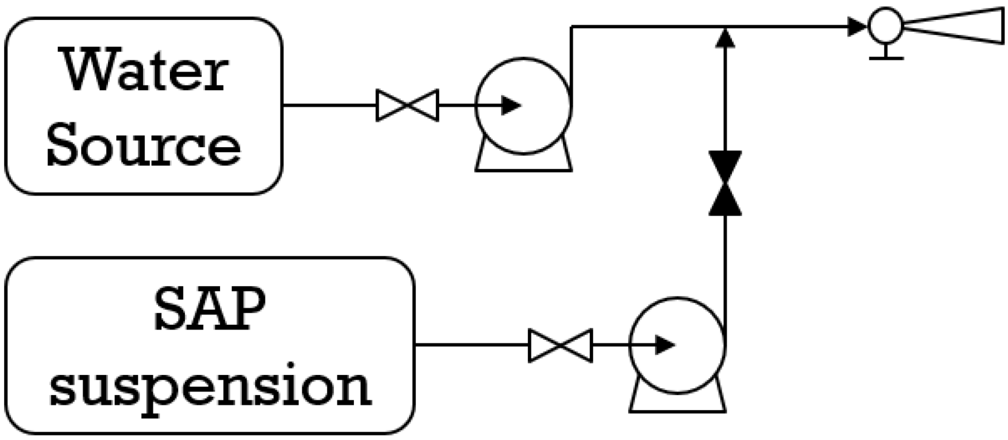


Figure 2.2 Structure chart of the sprinkling system

The suspension supply system includes a SAP suspension tank, a pump and a flowmeter to control the flow of the SAP suspension. In principle, a 3-4gallon container such as bucket that can be easily moved by a normal adult is the good choice for the SAP suspension tank. But the size of the tank can be various based on houseowners need and preference. A cover to the SAP suspension tank is recommended but not needed. Besides, A small submersible pump is enough for the suspension supply system since the mixing ratio of water to SAP suspension is normally 10:1 to 20:1. Finally, the flow rate of the suspension will not exceed 0.3 GPM, so a 0.1-1 GPM flowmeter would be suitable for the system.

The spray system is the main structure for spraying and for water and suspension to mix. Although house owner can build this system by purchase tube, spray nozzle and other equipment, the recommended solution is to use a power washer. The commercially available power washer always has a soap nozzle which can also be used for SAP suspension and its inside structure and nozzle fulfills our need for the spray system. Since the power washer also include a water pump, the water supply system and spray system are combined in a power washer. The choice of the power washer should base on the area of the house and will be discussed in the later section.

2.3 Supplies Checklist and Purchase Channels

While most of the supplies can be bought on Amazon, Ebay or Home Depot, some materials and equipment can be bought with a low price on other purchase channel. These information are summarized in the following tables.

Table 2.1 Personal Protective Equipment Checklist

Material/Equipment	Brand	URL
PPE kit	Raven	https://www.homedepot.com/p/Raven-Essential-Safety-Kit-3-Ply-Face-Mask-Plus-3-Sets-of-Heavy-Duty-Nitrile-Gloves-Plus-3-Individual-Packed-Sanitizing-Wipes-RMSK3P-S/315463179
Disposal Workwear	Boen	https://www.homedepot.com/p/BOEN-Coverall-Hood-Elastic-Cuffs-Chemical-Protective-Disposable-Workwear-for-Cleaning-Painting-Manufacturing-Blue-Size-3X-CA-B-3X/313282452
Safety Goggle	HDX	https://www.homedepot.com/p/HDX-

Table 2.2 SAP Suspension Supplies Checklist

Material/Equipment	Brand	URL
Canola Oil	Nature's Oil	https://www.bulkapothecary.com/product/raw-ingredients/bulk-natural-oils/canola-oil/?sku=RAW%20BAY-bna-136drum
Fumed Silica(CAB-O-SIL)	Flexkrete	https://www.zoro.com/flexkrete-additve-concrete-silica-10-lb-bag-white-fk-mp-5/i/G8985803/feature-product?utm_source=google&utm_medium=surfaces&utm_campaign=shopping%20feed&utm_content=free%20google%20shopping%20clicks&gclid=Cj0KCQjw4cOEBhDMARIsAA3XDRh8IGQHAO5lQwXOEZ5gX6zXEpquQFUUaFd_DLmRiHb6IWYaWfwx9HYaAnW-EALw_wcB
Sodium polyacrlate	DiagNano™	https://www.cd-bioparticles.com/product/polyacrylate-pa-list-217.html
Span 80	Spectrum	https://www.grainger.com/product/6WYV0?gucid=N:N:FPL:Free:GGL:CSM-1946:tew63h3:20501231
Triton X-100	RPI	https://www.amazon.com/Triton-X-100-Reagent-Grade-Gallon/dp/B00I320JH6/ref=sr_1_2?dchild=1&gclid=Cj0KCQjw4cOEBhDMARIsAA3XDRiiPt41ZQDcVX9cuH-cgLYxZxVQennSG3kuyx5eA0nyuBBmz1YaFN0aAo7sEALw_wcB&hvadid=174242021956&hvdev=c&hvlocphy=9007901&hvnetw=g&hvqmt=e&hvrand=3813929831189060942&hvtargid=kwd-3413416948&hydadcr=948_9642200&keywords=triton+x-100&qid=1620187711&sr=8-2

Table 2.3 Sprinkling System Equipment Checklist

Material/Equipment	Brand	URL
Power washer/ Light duty*	Ryobi	https://www.homedepot.com/p/RYOBI-1-600-PSI-1-2-GPM-Electric-Pressure-Washer-RY141612/301004462
Power washer/ Medium duty**		https://www.homedepot.com/p/RYOBI-2000-PSI-1-2-GPM-Cold-Water-Electric-Pressure-Washer-RY142022VNM/313760964
Power washer/ High duty***		https://www.homedepot.com/p/RYOBI-3000-PSI-2-3-GPM-Honda-Gas-Pressure-Washer-RY803001/303316335
Bucket	Homedepot	https://www.homedepot.com/p/The-Home-Depot-5-Gal-Homer-Bucket-05GLHD2/100087613
Tube	Everbilt	https://www.homedepot.com/p/Everbilt-3-4-in-O-D-x-1-2-in-I-D-x-10-ft-Clear-PVC-Vinyl-Tube-769299/207144355
Submersible pump	Vivosun	https://www.amazon.com/VIVOSUN-Submersible-Fountain-Aquarium-Hydroponics/dp/B07L54HB83/ref=sr_1_omk_6?crid=2A9OIW168NQWM&dchild=1&keywords=submersible+pump&qid=1620236521&sprefix=submer%2Caps%2C158&sr=8-6
Flow Meter	Bnyzwot	https://www.amazon.com/dp/B07VFK6KMN/ref=cm_sw_em_r_mt_dp_ZZBAMEY4063QXCR01FDS?_encoding=UTF8&psc=1

*: Up to 1899 PSI, suitable for small houses.

**: 1900-2799 PSI, suitable for normal houses.

***: 2800+ PSI, suitable for large houses with a second floor.

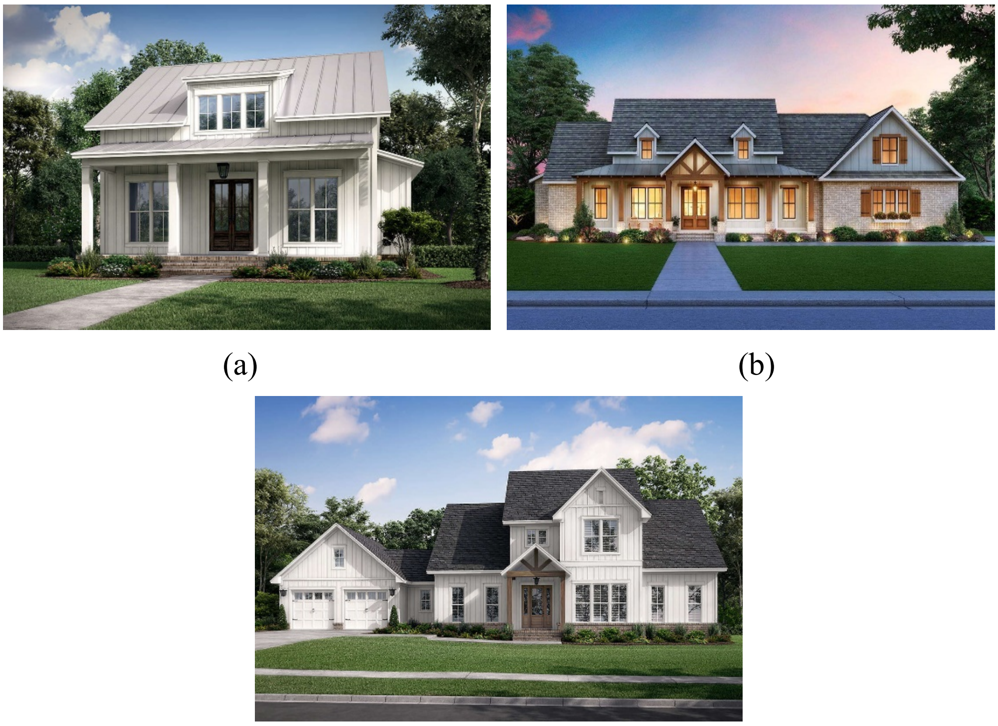
3 Results and Discussion

3.1 Cost Accounting

Table 3.1 Cost Accounting

Material/Equipment	Small		Medium		Large	
	Amount	Price/$	Amount	Price/$	Amount	Price/$
Canola Oil	100.7Kg	308.8	167.9Kg	514.6	235.1Kg	720.4
Fumed Silica(CAB-O-SIL)	2.98Kg	82.9	4.97Kg	138.1	6.96Kg	193.3
Sodium polyacrlate	66.72Kg	586.6	111.2Kg	977.6	155.68Kg	1368.6
Span 80	4.03Kg	362.5	6.73Kg	604.1	9.42Kg	845.7
Triton X-100	1.06Kg	19.5	1.76Kg	32.5	2.46Kg	45.5
Total SAP Suspension Material Fee*	1360.3		2266.9		3173.5	
Power washer	Light duty	99	Medium duty	199	High Duty	369
Bucket	1	3.78	1	3.78	1	3.78
Tube	1	9.22	1	9.22	1	9.22
Submersible pump	1	22.99	1	22.99	1	22.99
Flow Meter	1	24.59	1	24.59	1	24.59
Total Sprinkling System Equipment Fee	159.58		259.58		429.58	
PPE kit	1	11.77	1	11.77	1	11.77
Disposal Workwear	1	17.99	1	17.99	1	17.99
Safety Goggle	1	3.97	1	3.97	1	3.97
Total Personal Protective Equipment Fee	33.73		33.73		33.73	
Total	1553.61		2560.21		3636.81	

For a single-family home, the medium size is 2,301 square feet [U.S. Census Bureau, 2020]. In this way, we choose three different size of houses to do the cost accounting: A 1,200 square feet small size house, a 2,300 square feet medium size house, a 3,000 square feet large size house with a second layer. The area here refers to the internal floor area.



(a) (b)

(c)

Figure 3.1 Example of small size(a), medium size(b), large size(c)

The roof area and exterior siding area used to estimate the material need for medium size houses come from the fact given in a NAHB 2004 report [Pflieger, 2004]. The roof area and exterior siding area of small and large size houses is estimated based on the exterior siding length and building coverage, and those data are calculated based on the floor plan provided by America's Best House Plans, Inc..

Table 3.2 Data used in cost accounting

Item	Medium	Small	Large
Floor area/ ft^2	2,300	1,200	3,000
Building coverage/ ft^2	2,300	1,200	2,600
Exterior siding length/ Foot	204	170	375
Roof Area/ ft^2	3,103	1,619	4,047
Exterior siding area/ft^2	3,206	2,672	5,893

The thickness of the fire-retardant gel layer used in cost accounting is 0.5 inch and the mixing ratio of water and SAP suspension is 20:1. The amount of material listed in the table 3.1 is 50% exceed the exact amount needed to spray the roof and exterior siding. The exceed materials are used to spray on the nearby vegetation and other combustible goods.

The median cost to implant the whole system is $2560, which is nearly equal to 10% of the cost for home hardening and 25% of the cost to install the basic Fire-retardant based defense systems. Although this system can only provide a temporary enhancement to the wildfire resistance of the house, the cost is much more affordable than the other two considering the frequency of the wildfire.

3.2 Flame Test

We paint a 0.5-inch-thick fire-retardant gel layer on a plywood and a blowtorch fueled with butane and with a flame temperature approximately 1,430 °C is used to test the fire resistance of the material.

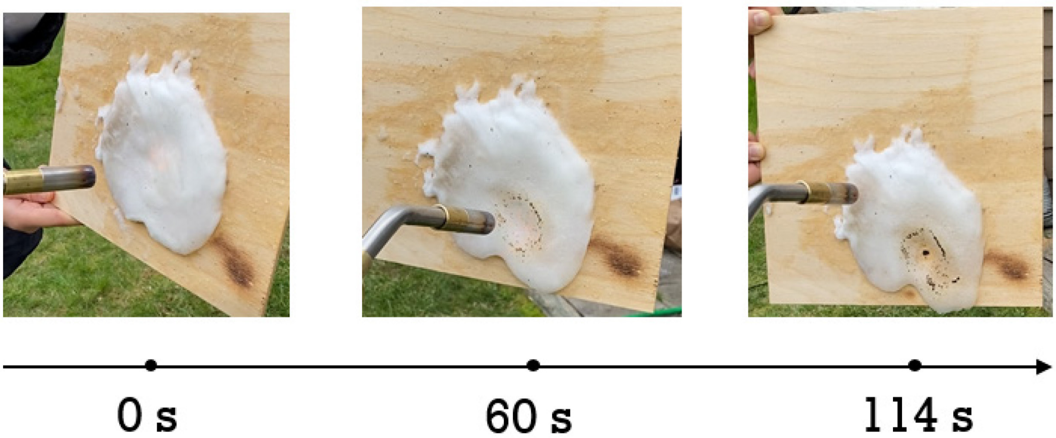


Figure 3.2 Flame test

The fire-retardant gel layer survived under the butane torch for 114s, while the control group, a bare plywood, carbonized as soon as contact with the flame. We also noticed that the gel layer performed a self-healing capability after we removed the flame. This cause of this phenomenon may be the combined effect of gravity and the moisture transfer and the rehydration of SAP. Some of the upper gel moved downward to cover the burned through part because of the gravity. Also, the moisture transfer between the hydrous gel around the burned through part and the dry SAP particles help the SAP to rehydrate and recreate the protective layer. The test suggests that the gel layer can provide an enhancement to the wildfire resistance of the house.

3.3 Spray test

We connected all the equipment as we mentioned in the last chapter and tried the sprinkling system. However, the result is not very satisfactory. Only a few gel particles remained on the plywood and most of them ran off to the ground. Although we did not get the gel sprayed on the plywood, we successfully collected some formed gel formed the ground. The test suggests that the idea to spray the gel is feasible, but the sprinkling system needs further improvement.

Figure 3.3 Spray test

4 Conclusion

i. In this project, we successfully prepared a stable super-absorbent polymer suspension that can be used as fire retardant, prototyped the sprinkling system used for the SAP suspension.

ii. We completed the cost accounting for the system. The median cost to implant the system is $2560.21, which is nearly equal to 10% of the cost for home hardening and 25% of the cost to install the basic Fire-retardant based defense systems.

iii. We tested the fire resistance of the fire-retardant gel layer. The fire-retardant gel layer survived under the butane torch for 114s, demonstrated that the gel layer can provide an enhancement to the wildfire resistance of the house.

iv. We tried the sprinkling system and collected some useful data that can be used in further research.

5 Future Works

The results we got from this project demonstrated that this home defense strategy has a great potential to develop. However, due to the time constraints and limited condition, the overall picture of this project has not been fully explained. This project can be further developed such as the following:

- Improve sprinkling system – The current sprinkling cannot achieve the goal we want. Further improvement can focus on the design of the spray nozzle.

- Effect of different surfactant – The surfactants acting as the dispersant and wetting agent may have a better choice. Further experiments can deepen the understanding of the effect of different surfactant.

- Further flame test – The tests conducted in this project are small-scale experiments. A larger-scale experiment using a 1:1 size house model that operate in a designed environment can further explained the effectiveness of the system and reveal more useful data.

Reference

Cal Fire (2020). 2020 California Department of Forestry and Fire Prodection. 2020 Incident Archive. Retrieved from https://www.fire.ca.gov/incidents/2020/

van Eeden, L., et al (2020). Austraila’s 2019–2020 bushfires: The wildlife toll - interim report. The World Wildlife Fund for Nature, Sydney, p. 5

Matthew, A. and Baker, N. (2020). One year since Australia's devastating wildfires, anger grows at climate change 'inaction'. NBC News. URL https://www.nbcnews.com/science/environment/one-year-australia-s-devastating-wildfires-anger-grows-climate-change-n1256714

Mulkern, A. (2020). Fast-Moving California Wildfires Boosted by Climate Change. Scientific American.

Westerling, A. L. (2016). Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1696), 20150178.

Abatzoglou, J. T. and A. P. Williams (2016). "Impact of anthropogenic climate change on wildfire across western US forests." Proceedings of the National Academy of Sciences 113(42): 11770-11775.

Radeloff, V. C., et al. (2018). "Rapid growth of the US wildland-urban interface raises wildfire risk." Proceedings of the National Academy of Sciences 115(13): 3314-3319.

Mietkiewicz, N., Balch, J. K., Schoennagel, T., Leyk, S., St Denis, L. A., & Bradley, B. A. (2020). In the line of fire: consequences of human-ignited wildfires to homes in the US (1992–2015). Fire, 3(3), 50.

Stephens, S. L., Adams, M. A., Handmer, J., Kearns, F. R., Leicester, B., Leonard, J., & Moritz, M. A. (2009). Urban–wildland fires: how California and other regions of the US can learn from Australia. Environmental Research Letters, 4(1), 014010.

Gan, J., Jarrett, A., & Gaither, C. J. (2014). Wildfire risk adaptation: propensity of forestland owners to purchase wildfire insurance in the southern United States. Canadian Journal of Forest Research, 44(11), 1376-1382.

McFarlane, B. L., McGee, T. K., & Faulkner, H. (2012). Complexity of homeowner wildfire risk mitigation: an integration of hazard theories. International Journal of Wildland Fire, 20(8), 921-931.

Ager, A.A., Kline, J.D. and Fischer, A.P. (2015), Coupling the Biophysical and Social Dimensions of Wildfire Risk to Improve Wildfire Mitigation Planning. Risk Analysis, 35: 1393-1406.

Apostol, K. G., McAvoy, D., Sparks, A., Kuhns, M., Jones, C., & Zamora, D. (2018). Protect Your Home from Wildfire: Ember Awareness Checklist. Retrieved from https://digitalcommons.usu.edu/extension_curall/1979/

Quarles, S. L., Valachovic, Y. A. N. A., Nakamura, G. M., Nader, G. A., & De Lasaux, M. J. (2010). Home Survival in Wildfire-Prone Areas: Building Materials and Design

Considerations. http://dx.doi.org/10.3733/ucanr.8393 URL https://escholarship.org/uc/item/4vt8w5qk

Penman, T. D., Eriksen, C., Horsey, B., Green, A., Lemcke, D., Cooper, P., & Bradstock, R. A. (2017). Retrofitting for wildfire resilience: what is the cost?. International journal of disaster risk reduction, 21, 1-10.

Chiment, R. F. (2020). Economically Viable Methods for Wildfire Protection for Residential Homes in Santa Barbara County. Retrieved from https://digitalcommons.calpoly.edu/cmsp/386/

Brenkert-Smith, H., Champ, P. A., & Flores, N. (2012). Trying not to get burned: understanding homeowners' wildfire risk–mitigation behaviors. Environmental Management, 50(6), 1139-1151.

Mignon, A., Vermeulen, J., Snoeck, D., Dubruel, P., Van Vlierberghe, S., & De Belie, N. (2017). Mechanical and self-healing properties of cementitious materials with pH-responsive semi-synthetic superabsorbent polymers. Materials and Structures, 50(6), 1-12.

Edwin, T. S. (2003). Methods for preventing and/or extinguishing fires (U.S. Patent No. 7189337B2). U.S. Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US7189337B2/en?oq=7189337

U.S. Census Bureau. Characteristics of New Housing, 2020. Retrieved from https://www.census.gov/construction/chars/highlights.html#:~:text=The%20median%20 size%20of%20a%20new%20single%2Dfamily%20home%20sold,homes%20were%20started%20in%202019.

Pflieger, R., Reichle, D., & Shackford, J. (2004). Housing Facts, Figures and Trends 2004. Washington DC: National Association of Home Builders.